THE PROPERTIES OF AGGREGATE FOR DENSE GRADED BASE COURSE CONSTRUCTION

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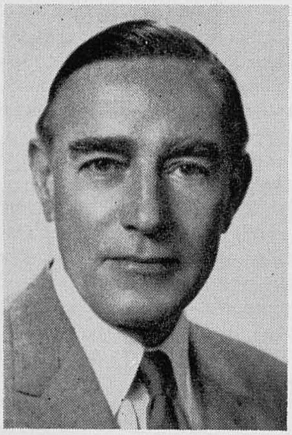
The purpose of this paper is to discuss several aspects of dense graded aggregate base course construction which are essential to obtain the best in performance and economy. There will be a short review of the requirements of a satisfactory foundation for these bases; a report of our research investigation on the desirable properties of the aggregate; a discussion of the effect of water; and finally, some comments on inspection procedure.



In a discussion of the properties of aggregate for base course construction, it is assumed that the road has been graded and drained, and that a firm foundation has been prepared to receive the base course. Sometimes these assumptions are not carried out in practice which may be a cause of failure of the pavement. While a road may be graded and drained, it may not necessarily have a suitable foundation for a base course. The foundation course, whether it be the subgrade or a subbase, should be constructed to line and grade, and must be firm. A soft, yielding foundation is unsatisfactory and should be corrected before the base course is placed. A yielding foundation, one that is soft or spongy, must be removed and replaced with firm material or must be stabilized by some additive which renders it firm. This is essential because for a base course to perform properly it must be compacted to a high density which is determined by laboratory tests and is obtained on the job by rolling. The required density cannot be obtained by rolling on a soft, yielding or elastic foundation. The foundation must be firm and solid.

A base course to perform satisfactorily must not have at any time an accumulation of water under it, within it, or on top of it. Opinions and construction practices differ as to the best foundation or subbase course to accomplish this objective. Some believe that if a foundation is solid or really of sufficient density it will not take up water while other believe that a readily drainable subbase is desirable. A drainable subbase is generally thought of as a granular layer with less than 5 per cent minus 200-mesh material laid to a compacted thickness of not less than 4 inches and with outlets through the shoulders spaced at frequent intervals to convey the water away. A base course of the proper gradation and compacted to the required high density is practically impervious. Therefore, to prevent the accumulation of water within the base, it must be adequately compacted. The accumulation of water on top of a base course is one of the most prevalent causes of unsatisfactory performance. If in the final shaping and rolling of a base course, an excessive amount of fines is produced on the surface and it is covered with a bituminous surfacing, water will accumulate in the interface of the two courses. When freezing and thawing takes place, about a quarter of an inch of mud will develop. In the spring, this soft layer allows a wave action under traffic to occur which will cause failure of the surface by alligator cracking. The best way to prevent this mud layer is to broom the completed base with a power broom to remove the fines and to present a clean, mosaic stone surface with no loose material. This surface should then be given an asphalt prime. The result is a stone to stone contact when the binder course is placed and no interposing layer is present for the accumulation of water.

Often the troubles that have occurred with flexible pavements have been attributed to "inadequate" base. An inadequate base may be lacking in sufficient thickness or it may be lacking in properties that are essential for satisfactory performance. For a base course to function properly, there must be good design, good construction, and good materials. The National Crushed Stone Association has been making research studies in their laboratories by means of the triaxial compression test on dense graded base aggregates in order to determine the properties that would assure satisfactory performance of crushed stone base materials. The Director of Research of the Kentucky Highway Department has been given a complete report on these studies. The following is an abstract of the more pertinent features of the paper relative to the use of crushed limestone.

Since it was desirable to test numerous gradations with the maximum size of aggregate varying from 3/8 to 2 in., the Texas Method of Triaxial Compression Test seemed to offer the most promise because the triaxial compression test measured fundamental properties; the test was made on materials in their worst condition, namely, capillary saturation; a larger number of specimens could be tested; apparatus had been developed for testing aggregates in the desired range of sizes; the equipment was available at reasonable cost; and finally, the Texas Highway Department had good correlation of the test results with field performance.

Gradations

Dense graded crushed stone bases have come into widespread use in recent years because of ease of construction through improved methods and ease of inspection and control. Furthermore, these bases can be built true to line and grade with exceptional smoothness; consequently, subsequent surfacing courses have excellent riding qualities. The stone should be of good quality, carefully graded, mixed with an optimum amount of water. It should be machine spread on a firm base and compacted to a high density. Experience has shown that for crushed stone to function properly a continuous grading should be used such as one conforming with Talbot's Equation $P = (d/D)^n$ in which P is the percentage passing any given sieve, d, and D is the maximum size. The value of n is usually between $1/3$ and $1/2$. For practical construction it is believed that n should approach $1/3$. However, for the laboratory investigation herein reported, the gradings were either with n having a value of $1/3$ except for the amount passing the No. 200 sieve, which was usually reduced to non-frost susceptible levels, or a value of $1/2$. In general, the gradations resulting from either of these exponential values were within the requirements of most state highway specifications for base course aggregates.

Variables Studied

Using the afore described testing procedure and analysis, the following studies were made on continuous gradings with uniform distribution of various size fractions:

A. Effect of Maximum Size of Aggregate
B. Effect of Fines—Material Passing No. 200 Sieve
C. Effect of Plasticity

The Effect of Maximum Size of Aggregate

A series of triaxial compression tests was made on crushed stone with 3/8, 3/4, 1, and 1½ in. maximum sizes and complying with Talbot's equation for n = 1/3 and with 3/4, 1, and 1½ in. maximum sizes with n = ½. The gradations used are given in Table I and a summary of the test data are given in Table Ia. When the Mohr failure or rupture envelope, which is the shear strength versus normal stress relationship, was plotted for each of the maximum sizes and compared with the Texas Classification system, all were satisfactory base course materials, Figures 1 and 2. Yet, some were better than others. The rupture envelopes cross the ordinate of zero normal stress at different points which is caused probably by the "apparent cohesion" that exists in well graded mixes when moist. It may be observed that "apparent cohesion" occurred to a greater extent in mixes with the

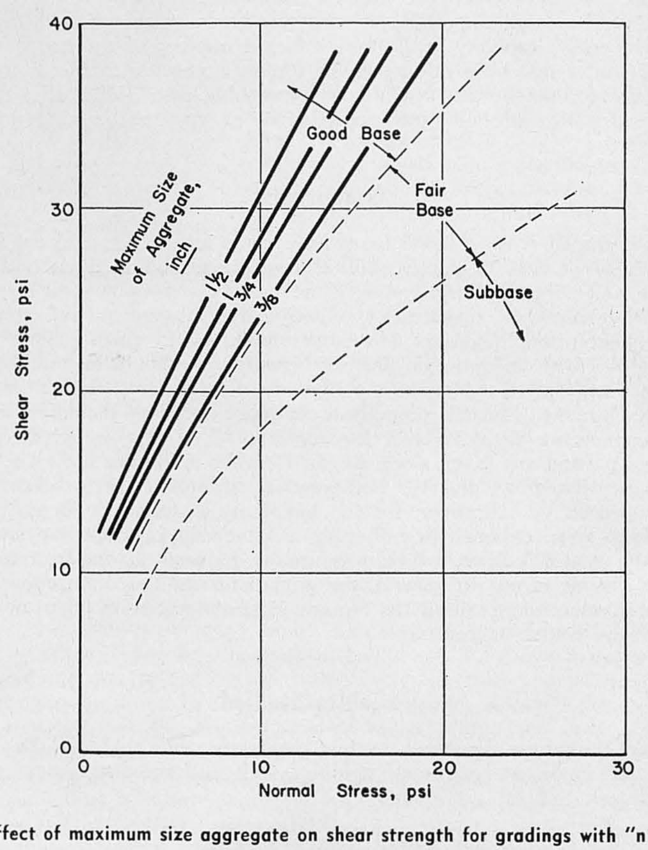


Fig. 1—Effect of maximum size aggregate on shear strength for gradings with "n = 1/3".

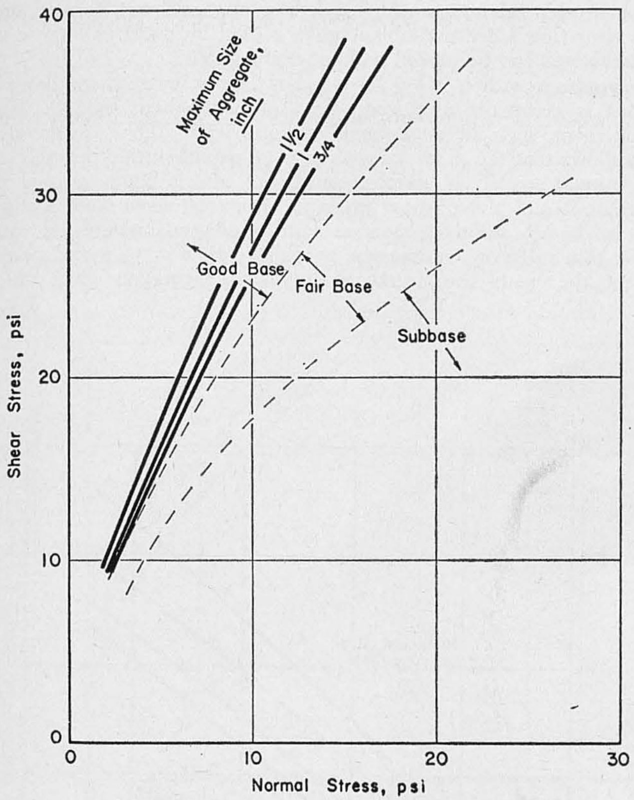


Fig. 2—Effect of maximum size aggregate on shear strength for gradings with "n = ½".

larger sized aggregate. The slope of the lines, peak angle of internal friction, is also slightly greater with the increase in maximum size. Aggregate interlock is greater for the gradings with the larger aggregate; the larger aggregate forms what may be described as "obstacles" in the planes of failure which increases the strength of the mix.

Further analyses showed some interesting and significant differences. When the maximum normal stress is plotted against the lateral pressure, the greater the maximum size, the greater the load carrying capacity for any given lateral pressure, Figures 3 and 4. Probably of more importance than ultimate strength is the greater rigidity afforded by the larger maximum size aggregate. This is shown in Table 1b and in Figure 5 where the per cent strain is plotted against the maximum size of aggregate. For a given normal load and lateral pressure, the per cent strain reduces as the maximum size of aggregate increases. Since the riding qualities of a pavement are dependent upon having a base that will not deform under load, it becomes clear that a distinct advantage is gained by using as large a maximum size of aggregate as can be placed without segregation.

Those gradings with n = ½ have a low mortar content so that a stone to stone contact is essentially produced which gives the high rigidity. For a base with a thick cover, such material should perform well. Yet, a review of the data in Table II shows that the gradings with n = ⅓ would sustain a higher maximum normal pressure at any given lateral pressure and, also, a higher normal stress at 2 per cent strain at any given lateral pressure. It would seem from a study of the data that for heavy surfacing courses both gradations would be satisfactory; however, for thin surfacing courses, the gradings with n = ⅓ would be the better. In any event, the use of the largest maximum size aggregate gives the strongest base.

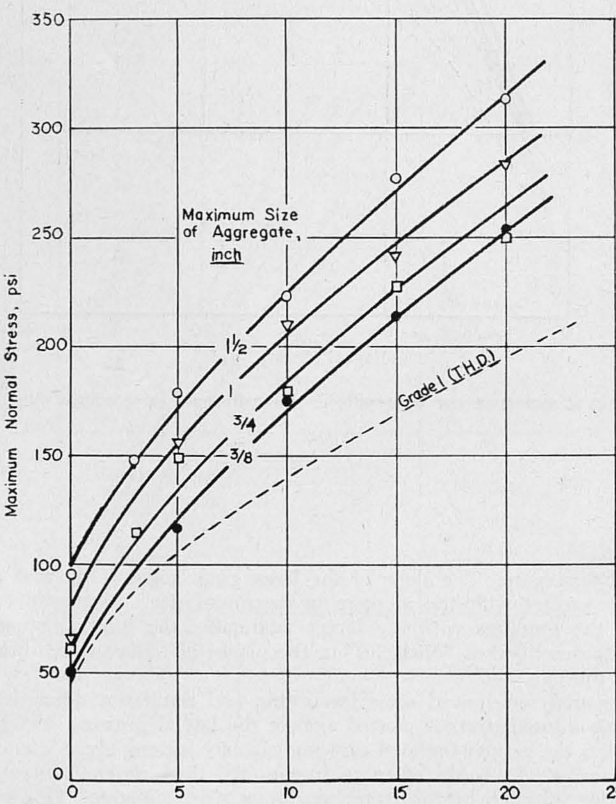


Fig. 3

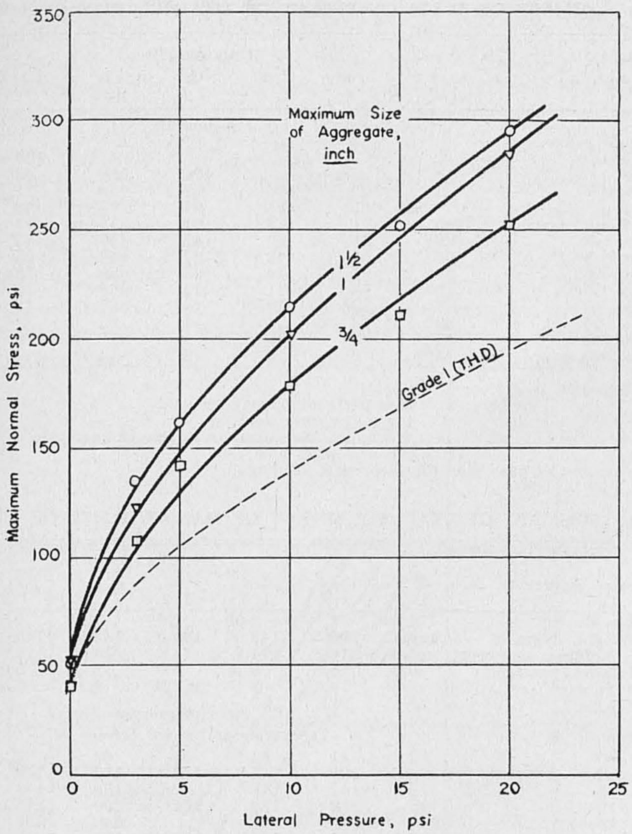


Fig. 4

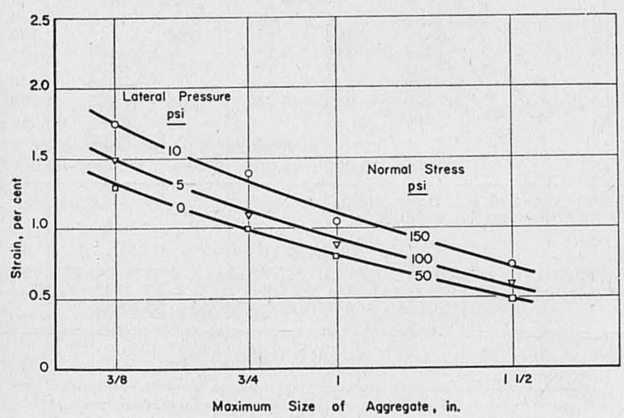


Fig. 5—Per cent strain vs. maximum size of aggregate at constant lateral pressure and a given normal stress for grading "n = 1/3".

TABLE I. SUMMARY OF TESTS ON EFFECT OF MAXIMUM SIZE OF AGGREGATE*

	Data on Mixes						
Maximum size, in.	3/8	3/4	3/4	1	1	1 1/2	1 1/2
"n"	1/3	1/2	1/3	1/2	1/3	1/2	1/3
	Gradation						
Total per cent passing							
1 1/2 in.						100	100
1 in.				100	100	82	86
3/4 in.		100	100	87	90	71	78
1/2 in.		82	87	71	79	58	69
3/8 in.	100	71	79	61	71	50	62
No. 4	79	50	63	43	57	35	50
No. 8	63	35	49	31	44	25	38
No. 16	50	25	40	22	36	18	31
No. 30	40	18	31	15	28	12	24
No. 40	36	15	28	13	25	11	22
No. 50	33	13	24	11	22	9	20
No. 100	25	9	20	8	18	6	16
No. 200	14**	6	16	5	14	4	12

* Talbot's Equation is $P = (d/D)^n$

where: P = total per cent passing sieve, d

d = any given sieve opening

D = maximum sieve opening or size of aggregate

n = exponent of 1/2 or 1/3

** A lesser amount of fines than the theoretical gradings

TABLE IA. SUMMARY OF TESTS ON EFFECT OF MAXIMUM SIZE OF AGGREGATE

	Mix Data						
Maximum Size Aggregate, in.	3/8	3/4	3/4	1	1	1 1/2	1 1/2
"n"	1/3	1/2	1/3	1/2	1/3	1/2	1/3
Bulk Specific Gravity	2.69	2.69	2.69	2.69	2.68	2.69	2.68
Dry Unit Weight, lb/cu ft[1]	144.4	140.5	143.0	144.3	145.0	145.0	146.0
Voids after Molding, per cent	14.0	16.3	14.8	14.0	13.2	13.9	13.0
Molding Moisture, per cent	6.0	5.2	5.7	5.0	5.2	5.0	4.8
Moisture at Time of Test, %	5.8	4.4	5.1	3.9	4.7	3.5	4.2
	Triaxial Compression Test						
Lateral Pressure, psi	Maximum Normal Stress, psi						
0	52	41	62	54	63	52	95
3	....	108	115	123	142	136	147
5	116	142	148	....	156	162	178
10	175	179	178	202	209	215	222
15	213	210	227	....	240	252	276
20	252	252	284	285	282	296	312
25	287	....	....	....	....	....	....
	Normal Stress, psi at 2 per cent strain						
0	51	*	58	*	*	*	*
3	....	106	109	120	142	126	146
5	114	140	143	....	154	151	178
10	163	167	160	187	209	193	221
15	186	192	220	....	239	230	275
20	215	235	242	258	275	266	310
25	230	....	....	....	....	....	....
	Modulus of Deformation, psi						
20	12,000	20,000	14,000	20,000	20,000	22,000	23,000

* Maximum stress occurred at a lesser strain.

[1] Determined immediately after molding.

TABLE 1B

PER CENT STRAIN OR DEFORMATION OF MATERIALS WITH DIFFERENT MAXIMUM SIZE OF AGGREGATE FOR GRADING WITH N = 1/3 AT CONSTANT LATERAL PRESSURE AND A GIVEN NORMAL STRESS

Maximum Size of Agg., in.		3/8	3/4	1	1 1/2
Lateral Presure psi	Normal Stress psi	Deformation, per cent			
0	50	1.30	1.00	0.80	0.50
5	100	1.50	1.10	0.87	0.60
10	150	1.75	1.40	1.05	0.75

The Effect of Fines—Material Passing No. 200 Sieve

The effect of the quantity of fines passing the No. 200 sieve on the stress-strain characteristics of dense graded crushed stone base material was investigated by obtaining ¾ in. maximum size crushed stone that was produced for a state highway job and varying the amount of fines 1, 4.5, 9, 13, and 20 per cent passing the No. 200 sieve. The aggregate was limestone with the material passing a No. 40 sieve being limestone of the same quality as the parent rock and non-plastic. A tabulation of the triaxial compression test data is given in Table III and a graphical presentation is made in Figures 6, 7, and 8.

All of these gradations would make satisfactory base courses according to the Texas Classification Chart, Figure 6, and this is in agreement with some base course specifications. However, there is a large difference in the load carrying capacity of these gradations. Their rating, best to worst, is 9, 4.5, 13, 1, and 20 per cent passing the No. 200 sieve, Figure 7. Probably the most significant

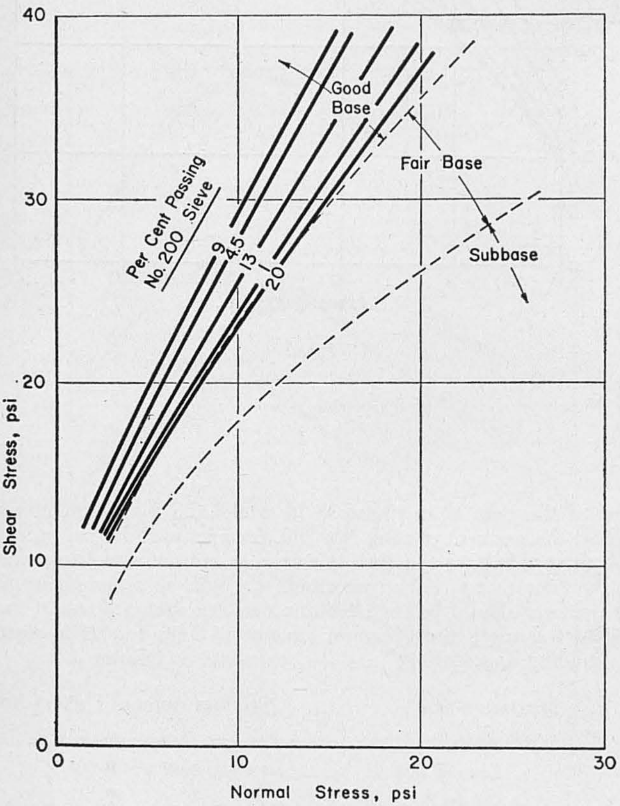


Fig. 6—Effect of amount passing No. 200 sieve on shear strength.

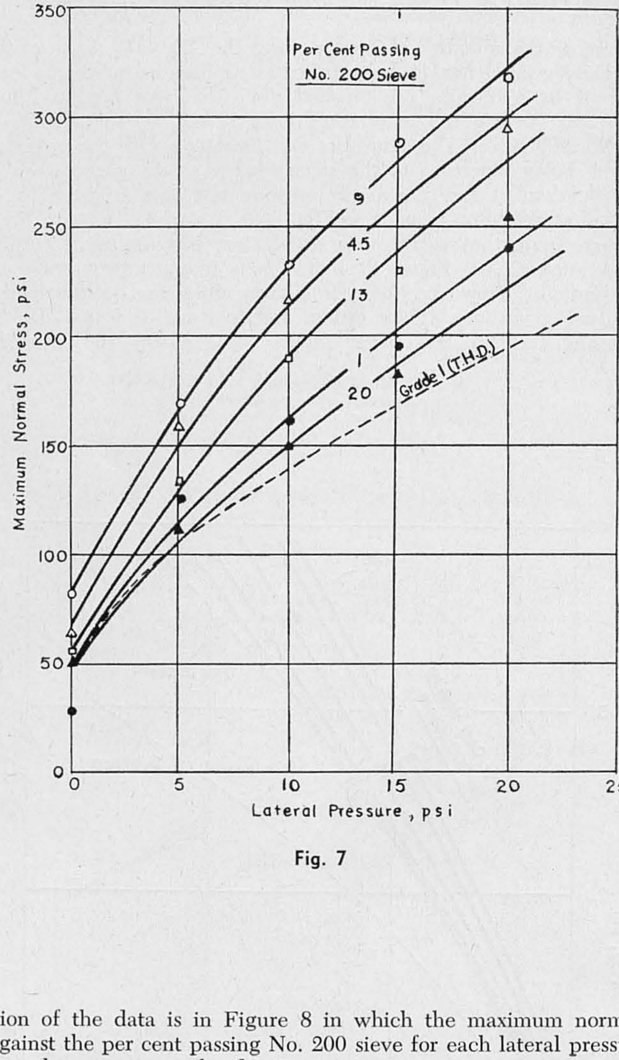


Fig. 7

presentation of the data is in Figure 8 in which the maximum normal stress is plotted against the per cent passing No. 200 sieve for each lateral pressure. Superimposed on these curves is the density curve at optimum moisture content. The curves clearly show that to obtain maximum strength an optimum amount of fines of about 9 per cent should be used for this size aggregate. Since 3/4 in. maximum size aggregate was used, the optimum amount of fines for other maximum sizes and with a grading approaching "n = 1/3" calculate as follows:

Maximum Size	*Optimum Amount Passing No. 200*
3/4 in.	9
1 in.	8
1½ in.	7
2 in.	6

An essential requirement in the construction of these base courses is the control of density. It can be readily seen from the curve in Figure 8 that high density would be difficult to obtain with a low percentage of lines but may be easily obtained wth a wide range in fines tending towards excessive amounts. An excessive amount of fines would not only lower the load carrying capacity of a base but may also make it frost susceptible. It is indicated, therefore, that any density requirements should be established on a specified range in amounts passing the No. 200 sieve, and confirms the specification requirements of several states that the amount passing the No. 200 sieve shall be between 5 and 12 per cent as being the proper practical range for this fine material.

The Effect of Plasticity

For many years almost all specifications required that the plasticity index should be not more than 6. In the production of base course material some state highway departments have permitted the use of weathered rock which readily

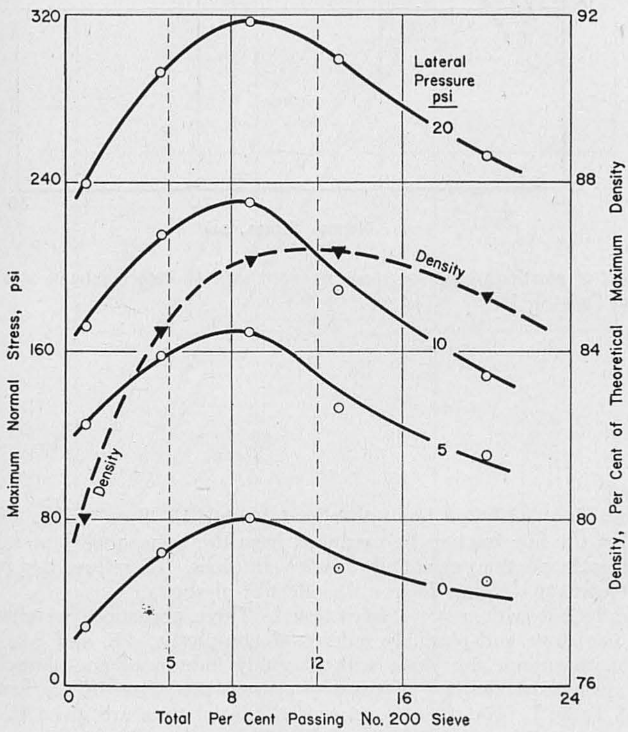


Fig. 8—Relationship of strength and density for material with different amounts passing No. 200 sieve.

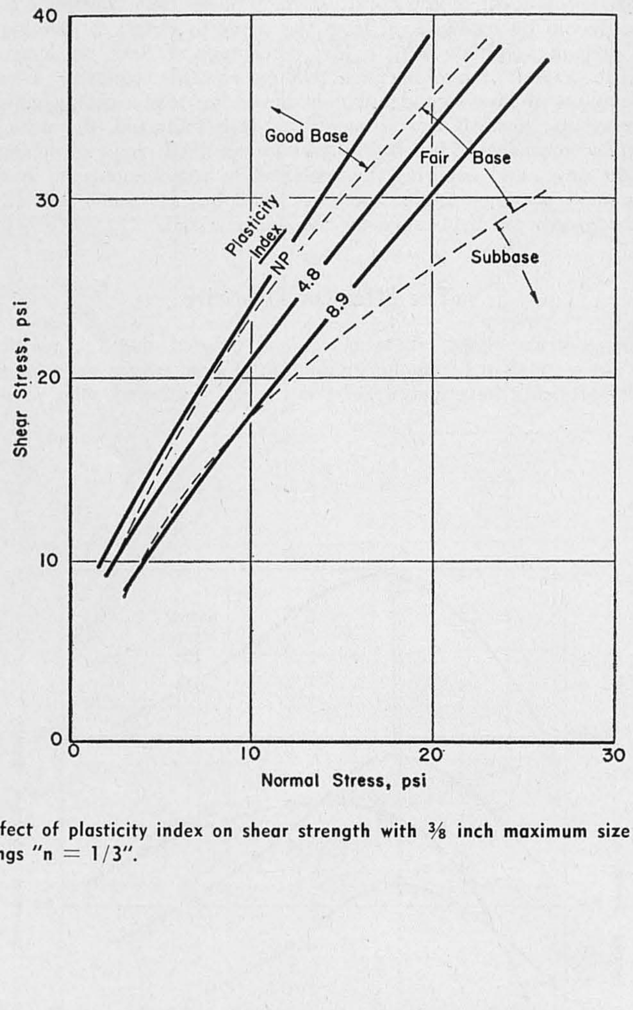


Fig. 9—Effect of plasticity index on shear strength with 3/8 inch maximum size aggregate and gradings "n = 1/3".

crushed into fines and possibly rather variable plastic fines, while other states required that the fine fraction be produced from the same quality of stone as the coarse aggregate fraction, essentially non-plastic fines. Therefore, this part of the investigation was to develop data on the effect of plasticity.

Six gradations with n = 1/3 were tested. Three gradations were with 3/8 in. maximum size stone and plasticity indexes of non-plastic, 4.8, and 8.9; and three with 1½ in. maximum size stone with plasticity indexes of non-plastic, 3.6, and 7.2. The mechanical analyses of these gradations are given in the first and last columns of Table I. The data on mixes and triaxial tests are given in Table III and in Figures 9, 10, 11, 12, 13, and 14. These data clearly demonstrate that plasticity may be a very detrimental characteristic of base course material. For the 3/8 in. maximum size aggregate, only the one with non-plastic fines can be considered a good base material, Figures 9 and 11. For the 1½ in. maximum size aggregate, the non-plastic mix and the one with a PI of 3.6 would be classified as good base material, but the mix with a PI of 7.2 could not be considered good base stone, Figures 10 and 12.

The effect of plasticity is more clearly shown in Table IIIa and in Figures 13 and 14 in which the per cent of strain is plotted against the plasticity index. With the high mortar or soil binder content in the ⅜ in. maximum size aggregate, the lubricating effect caused by plastic fines is apparent—the per cent strain for a given normal stress and lateral pressure increases rapidly with increased PI, Figure 13. For the 1½ in. maximum size aggregate the increase in strain is at a uniform rate as the PI increases for the range used in this investigation, Figure 14. With the large aggregate there is less mortar in the mix and the frictional resistance and aggregate interlock have a pronounced influence on the test results.

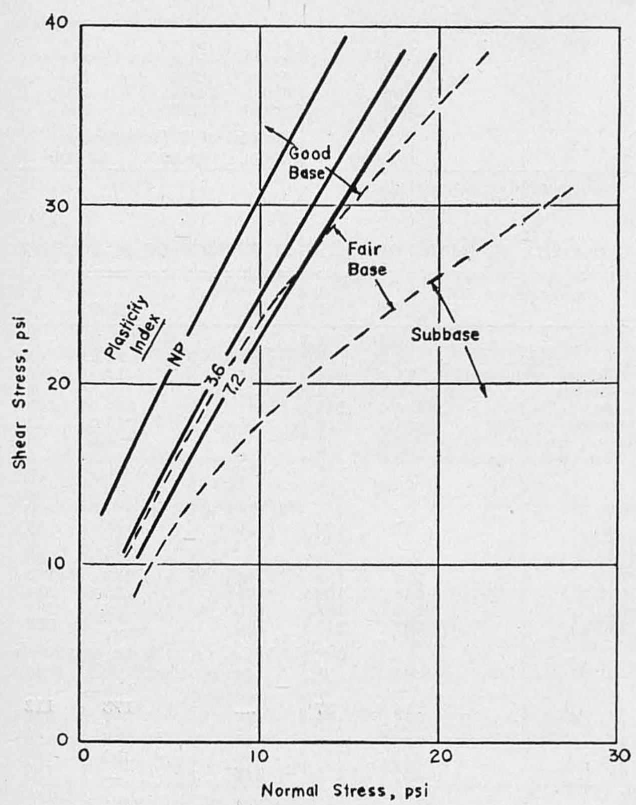


Fig. 10

TABLE II. SUMMARY OF TEST ON EFFECT OF FINES (PASSING NO. 200 SIEVE)

Gradation Passing No. 200 sieve	A 1	B 4.5	C 9	D 13	E 20
Total per cent passing					
1 in.	100	100	100	100	100
3/4 in.	98	98	98	98	98
1/2 in.	81	81	83	83	84
3/8 in.	66	67	69	70	72
No. 4	47	49	52	53	56
No. 8	37	38	43	45	48
No. 16	27	28	35	36	40
No. 30	20	21	27	30	35
No. 50	12	14	20	23	29
No. 100	5	8	13	17	24
No. 200	1	4.5	9	13	20
Bulk Specific Gravity	2.66	2.66	2.66	2.66	2.66
Dry Unit Weight, lb/cu ft[1]	132.6	140.1	143.0	143.3	141.5
Voids after Molding, per cent	20.1	15.6	13.8	13.6	14.7
Molding Moisture, per cent	4.5	5.0	5.0	5.0	5.2
Moisture at Time of Test, %	4.0	4.2	4.2	4.3	5.1
	Triaxial Compression Test				
Lateral Pressure, psi		*Maximum Normal Stress, psi*			
0	28	64	82	55	52
5	125	158	169	134	112
10	161	216	233	190	149
15	196	....	288	230	182
20	240	295	318	302	254
		Normal Stress, psi at 2 per cent Strain			
0	*	*	*	*	*
5	*	*	6	133	111
10	*	*	233	190	148
15	196	*	284	230	182
20	240	293	315	296	250
		Modulus of Deformation, psi			
20	25,000	25,000	26,000	23,000	19,000

* Maximum stress occurred at a lesser strain.
[1] Determined immediately after molding.

TABLE III. SUMMARY OF TESTS ON EFFECT OF PLASTICITY

Maximum Size Aggregate, in. "n"*	1/3	3/8 1/3	1/3	1/3	1 1/2 1/3	1/3
Plasticity Index	N. P.	4.8	8.9	N. P.	3.6	7.2
Liquid Limit	N. P.	17.7	19.7	N. P.	18.0	22.5
Passing No. 200, per cent	14	14	14	12	12	12
Bulk Specific Gravity	2.69	2.70	2.69	2.68	2.69	2.70
Dry Unit Weight, lb/cu ft[1]	144.4	141.1	141.3	146.0	147.5	146.0
Voids after Molding, per cent	14.0	16.4	15.8	13.0	12.1	13.0
Molding Moisture, per cent	6.0	5.5	6.0	4.8	5.0	5.9
Moisture at Time of Test, per cent	5.8	5.9	6.3	4.2	4.4	4.6
	Triaxial Compression Test					
Lateral Pressure, spi			*Maximum Normal Stress, psi*			
0	52	36	36	96	38	27
3	....	....	....	147	....	85
5	116	94	....	178	130	118
10	175	132	112	222	180	144
15	213	162	147	276	214	185
20	252	187	170	312	237	....
25	287	213	190	....	257	....
		Normal Stress, psi at 2 per cent Strain				
0	51	36	30	96	37	24
3	....	....	....	146	....	65
5	114	87	....	178	112	85
10	163	115	87	221	135	107
15	186	138	113	275	158	135
20	215	157	135	310	169	....
25	230	179	146	....	183	....
			Modulus of Deformation, psi			
20	12,000	10,000	8,000	23,000	10,000	7,009

* See Table I for detail of gradings.
[1] Determined immediately after molding.

TABLE IIIA

PER CENT STRAIN OR DEFORMATION OF MATERIALS WITH DIFFERENT PLASTICITY INDEX AT CONSTANT LATERAL PRESSURE AND A GIVEN NORMAL STRESS FOR GRADING WITH N = 1/3

		Maximum Size of Aggregate = 1 1/2 inch		
Plasticity Index		N. P.	3.6	7.2
Lateral Pressure psi	Normal Stress psi	Deformation, per cent		
0	20	0.20	0.72	1.01
5	80	0.55	1.30	1.80
10	140	0.65	2.10	3.30
		Maximum Size of Aggregate = 3/8 inch		
Plasticity Index		N. P.	4.8	8.9
Lateral Pressure psi	Normal Stress psi	Deformation, per cent		
0	30	0.60	0.85	1.60
5	70	0.85	1.25	....
10	100	1.02	1.50	2.60
15	140	1.40	2.05	3.10

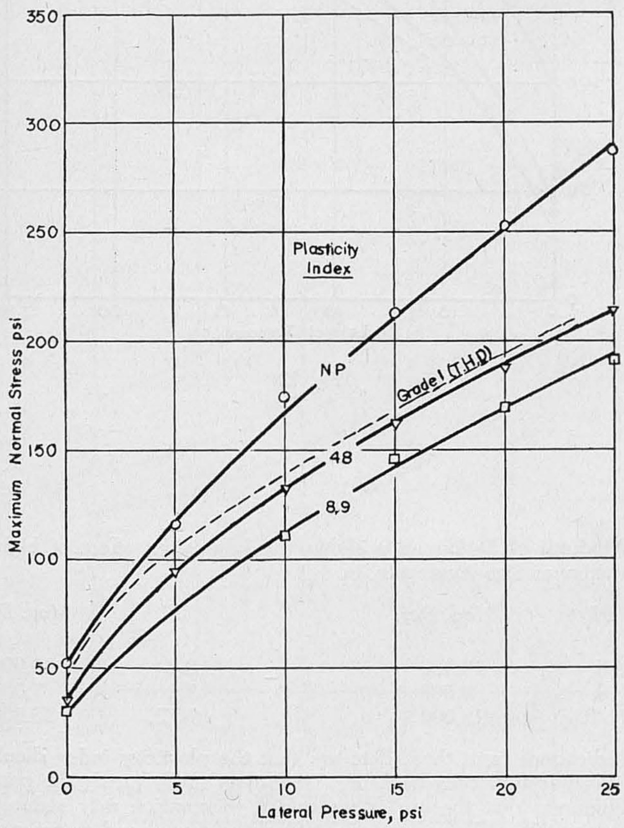


Fig. 11

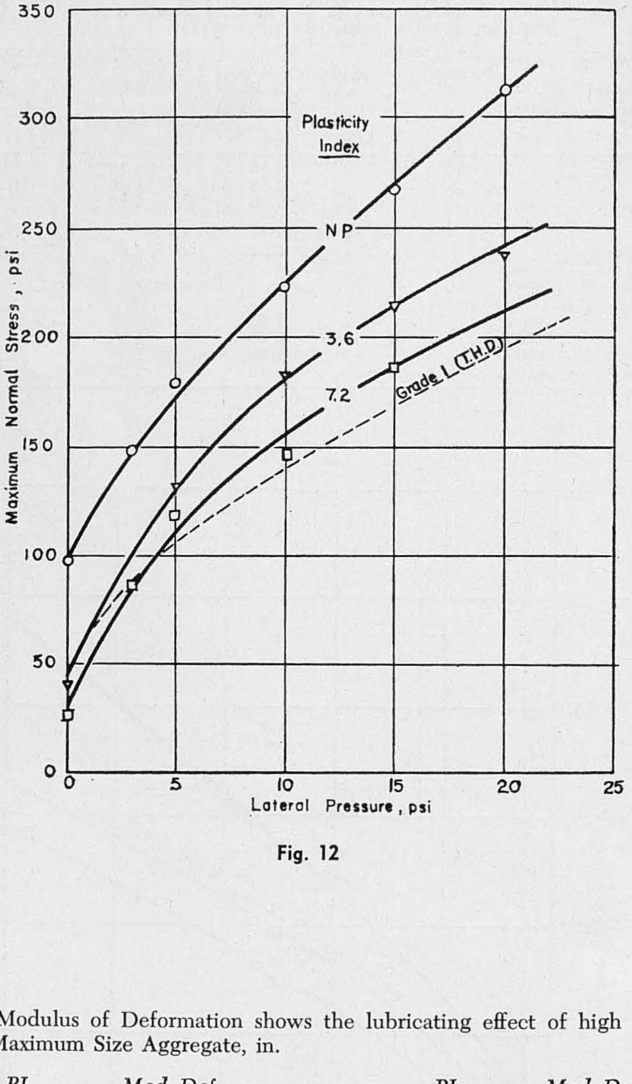


Fig. 12

The Modulus of Deformation shows the lubricating effect of high plasticity indexes: Maximum Size Aggregate, in.

PI	*Mod. Def.*	*PI*	*Mod. Def.*
3/8		1½	
4.8	10,000	3.6	10,000
8.9	8,000	7.2	7,000
N. P.	12,000	N. P.	23,000

The indications from these data are that the plasticity index should be kept as low as it can economically be done. These data surely justify the position taken by some engineers that the use of weathered rock which may reduce to plastic fines is detrimental to the performance of a base course and that the most satisfactory solution to the problem is to require that the fine aggregate portion be produced from rock of the same quality as the coarse aggregate. While a PI of 6 or less is widely accepted, it is concluded that the lower the PI, the better; and non-plastic material is best.

There has developed another requirement for dense graded aggregate base construction if good performance with maximum economy is to be obtained. This is good inspection procedure. Assuming aggregate of satisfactory quality, there are only three essential items to be controlled, gradation, moisture content, and density. The practice of some agencies of attempting to control gradation by sampling from the completed base has resulted in such costly methods to correct departures from specifications that this type of base is getting into disfavor. There have been occasions when the aggregate has been placed at the rate of 500 tons per hour and the contractor did not know until two weeks later if the material was

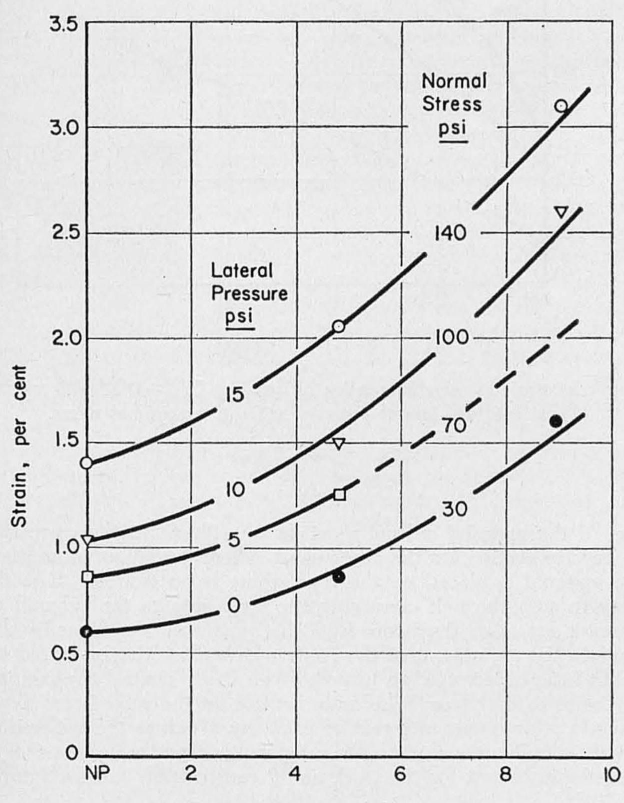


Fig. 13—Per cent strain vs. plasticity index for grading "n = 1/3 with maximum size of aggregate = ⅜ in. at constant lateral presure and a given normal stress.

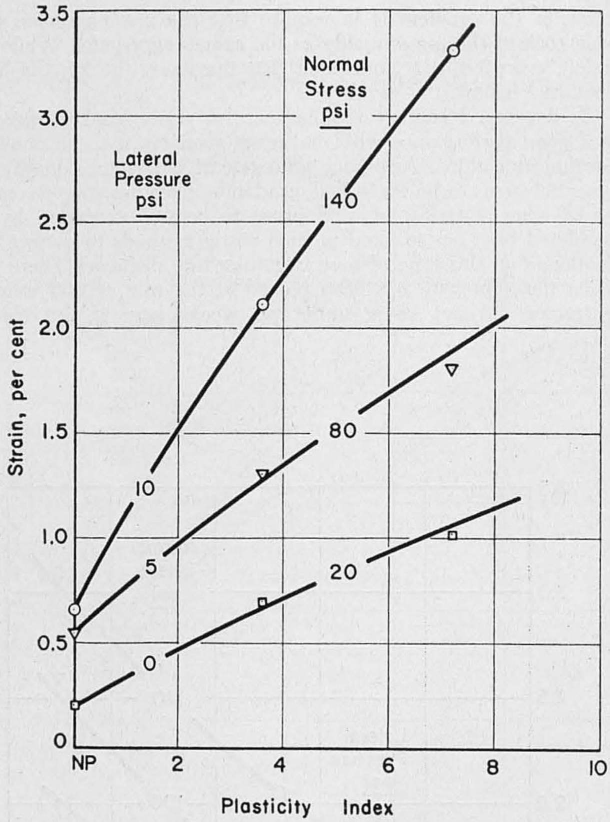


Fig. 14—Per cent strain vs. plasticity index for grading "n = 1/3" with maximum size of aggregate = 1½ at constant lateral pressure and a given normal stress.

acceptable. If the material did not meet the specifications, the corrective methods proved to be very costly. On the other hand, where gradation control is performed before the material is placed on the road, there is no trouble. It is the practice in one state to stop the belt conveying the aggregate to the pugmill and take a sample twice a day. Any departure from the specification is immediately corrected by a change in the adjustment of the feeds which place the separated sizes on the belt. With a little experience, an inspector can easily control the moisture content to be very close to optimum. The main control on the road is for density. Tests must be made at frequent intervals of each layer before the succeeding layer is placed. This simple procedure with competent inspectors assures a satisfactory job at a minimum of cost for the work under construction and for future work.

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With a good firm foundation, good aggregate of the proper gradation, compacted to high density, and good inspection procedure, these dense graded base courses can be built which will perform satisfactorily at the greatest economy.